# FACTORS WHICH INFLUENCE PVD PERFORMANCE IN SOFT CLAY CONSOLIDATION

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ABSTRACT: Soft clay consolidation is an important aspect to be considered for large construction projects undertaken in or near coastal areas. Pre-fabricated Vertical Drain or PVD has gained considerable importance in accelerating soft clay consolidation for major civil engineering construction projects worldwide, as it is economical with proven efficiency. However, there is still some confusion and uncertainty in selecting the right type of PVD for a particular project as well as the design procedure to be adopted. As a result, specification for PVD in many cases are made without considering many factors which may influence the performance of such drains for a project. This paper considers the PVD design theory and evaluates various parameters which influence PVD performance such as soil, soil disturbance due to installation, PVD materials etc., and recommends a procedure for PVD design and selection of PVD and installation method for a project.

KEYWORDS: soft-clay, PVD, consolidation

## 1 CONSOLIDATION THEORY

The main objective of soft clay consolidation with PVD is to achieve the desired degree of consolidation within a specified period of time. In classical one-dimensional consolidation theory (Terzaghi, 1943), consolidation due to vertical drainage only to natural drainage boundaries is considered. However, the classical one-dimensional consolidation theory can be extended to include vertical as well as horizontal or radial drainage taking place using vertical drains. Average degree of consolidation, U, then is calculated for combined vertical and radial drainage (Carrillo, 1942) as follows.

$U = 1 - (1- U_h)(1- U_v)$, where (1)

U = overall average degree of consolidation

$U_h$ = average degree of consolidation due to radial drainage

$U_v$ = average degree of consolidation due to vertical drainage.

A general equation for computing average degree of consolidation employing vertical drains due to horizontal or radial drainage was first proposed by Barron (1948) as follows.

$t = (D^2/8C_h)\, F(n)\, \text{In}\, (1/ (1 - U_h)$, where (2)

$C_h$ = coefficient of consolidation for radial drainage

t = time required to achieve $U_h$

D = diameter of the cylinder of influence of the drain

F(n) = drain spacing factor = $\ln(D/d_w) - 3/4$, where

$d_w$ = equivalent diameter of drain

Hansbo (1979) modified Barron's equation to suit consolidation with PVD, incorporating soil disturbance due to drain installation and drain resistance in the following 'general' case.

$t = (D^2/8C_h)\,(F(n) + F_s + F_r)\, \text{In}(1/(1–U_h))$, (3)

where

$F_s$ = factor for soil disturbance = $((k_h/k_s)-1)\ \ln(d_s/d_w)$, where

$k_h$ = the coefficient of permeability in the horizontal direction in the un-disturbed soil

$k_s$ = the coefficient of permeability in the horizontal direction in the disturbed soil

$d_s$ = diameter of the idealized disturbed zone around the drain

$F_r$ = factor for drain resistance = $\pi z (L - z) (k_h/q_w)$

z = distance below top surface of the compressible soil layer

L = effective drain length

$q_w$ = discharge capacity of the drain (at gradient = 1.0)

In the simplified 'ideal' case where soil disturbance and drain resistance are both ignored, the above general case simplifies to eqn-2 with only function of soil properties ($C_h$), design requirements ($U_h$) and design variables (D, $d_w$)

## 2 PARAMETERS WHICH INFLUENCE PVD PERFORMANCE

### 2.1 Drain Influence Zone, D

The time to achieve a given degree of consolidation is a function of the square of the diameter of the influence cylinder, D. D is a variable in the drain spacing factor, F (n), which is used in both the 'general' and 'ideal cases'. Unlike the other parameters which influence soil consolidation with the exception of $d_w$, D is a controllable variable since it is a function of drain spacing only. Vertical drains are usually installed in square or triangular patterns. The distance between the drains or drain spacing, S, establishes D with D = 1.13 S for Square Pattern and D = 1.05 S for Triangular Pattern. A triangular pattern is usually preferred, since it provides more uniform consolidation between drains when compared with equivalent square pattern.

### 2.2 Equivalent drain diameter, $d_w$

For practical considerations, assumption is made that both band shaped drain and a circular drain with the same circumference will result in similar soil consolidation. It is therefore reasonable to calculate the equivalent circular diameter of PVD to be:

$d_w = (2(a+b)/\pi)$, where a & b = width & thickness respectively of the rectangular PVD. For commonly available PVD at present, $d_w$ varies from 50 mm to 75 mm.

### 2.3 Drain discharge capacity, $q_w$

The drain discharge capacity is mainly influenced by the size of drain, soil confining pressure and effects of vertical compression on the shape of the drain. During consolidation, soil settlement causes the installed PVD to deform or 'buckle'. Considerable reduction in drain discharge capacity may result after buckling. It has been noticed that rigid drains cause larger reduction in discharge capacity as buckling starts at relatively lower vertical compression.

### 2.4 Horizontal Coefficient of Consolidation, $C_h$

$C_h = C_v (k_h/k_v)$, where

$k_v$ = vertical coefficient of permeability

As laboratory test results are very sensitive to soil sample disturbance, they depend very much on the quality of the soil samples tested. Special equipment and procedure are required for laboratory determination of $C_h$. Determination of $k_h$ is therefore usually made from special in-situ tests with good quality tests and equipment. Accuracy of results depends therefore on several factors and in many cases may not be quite reliable. It has been found that even tests carried out with care may result in variable values from the same site (Bergado et al, 2008).

Therefore, in most cases the practice is to determine $C_v$ from laboratory soil consolidation tests and estimate the value of $k_h/k_v$ from field and laboratory tests for PVD design.

Based on several field and laboratory tests in different soil conditions, for most sedimented clays the value of $k_h/k_v$ may vary from 2 to 5 (FHWA, 1986). Studies at the Indian Institute of Technology Madras (Sridhar et al, 2014) have shown that for coastal marine clays, a value of $k_h/k_v=2$ was found applicable, based on special laboratory tests and back analysis of instrument data from a number of project sites. $k_h/k_v$ back calculated from field instrument data suggest values between 2 and 3 for coastal marine clays (Radhakrishnan and Suriyanarayanan, 2010).

### 2.5 Soil Disturbance due to PVD installation

Soil consolidation due to combined horizontal and vertical drainage for the 'general case' considers both soil disturbance due to drain installation and drain resistance (eqn-3).

#### 2.5.1 *Disturbed soil zone or Smear zone, $d_s$*

For PVD installation, a steel mandrel is used to protect the drain during installation. The mandrel has a cross sectional area larger than that of the drain and it causes shear strains and displacements within the soil surrounding the drain. Accompanied by re-moulding of the surrounding soft soil, it increases the pore pressure and decreases the shear strength in the zone of disturbance (Holtz & Holme, 1973). Besides, the hydraulic conductivity of the disturbed soil is reduced and consequently the flow of pore water into the drain and rate of soil consolidation are reduced.

Many researchers have investigated the properties of the disturbed zone using laboratory investigation on large soil samples as well as by numerical methods. Studies by Chai and Miura (1999) and others suggest that the size of the smear zone may vary between 1 and 4 times the equivalent mandrel radius. FHWA (1986) suggests soil disturbed zone, $d_s$=5 to 6 times $r_m$, where $r_m$ is the radius of circle equivalent in area of mandrel cross section.

Evaluation of soil properties within the disturbed zone is extremely complex. In addition, the following factors also affect drain performance due to soil disturbance resulting from PVD installation which should be minimized as far as possible.

2.5.2 *Effect of Mandrel size and shape*

As disturbance increases with increase in mandrel cross sectional area, it should be as close to the drain cross sectional area to minimize soil displacement, but without affecting stiffness necessary to install the drain to design depths. Mandrel tip and anchor should be as tapered as possible to minimize disturbance. Most mandrels used currently are of rectangular in shape even though some use rhombic shaped mandrels. It has been considered that to minimize soil disturbance, mandrel cross sectional area should not exceed 65cm$^2$ (FHWA, 1986).

2.5.3 *Drain installation method*

The method of installation causes soil disturbance around the drain. Drain installation disturbs the soil and may reduce the shear strength of the deposit. Vibratory or jetting methods cause increased disturbance to soft soil than static pushing. PVD installation should therefore be by static pull down force where possible. For design purpose it may be considered that within the disturbed soil zone, the soil is completely remoulded.

### 2.6 PVD Material Parameters

Besides the above, material parameters of PVD used may influence PVD performance.

2.6.1 *Drain filter*

PVD filter fabric is exposed to ground water and remoulded fine grained soil after its installation. The fabric serves as a filter when the preloading increases pore pressures and the pore water seeps horizontally into the drain core. The potential therefore exists for the filter fabric to 'cake' or clog due to mobility of fines in the remoulded soil.

Filter permeability should be greater than that of the surrounding soil in order not to retard the pore water flow into the drain. However, very high permeability of filter may lead to large inflow of water and may not be effective in preventing fines from passing into the core. It may therefore be more effective to consider filter permittivity, which is defined as the volumetric flow rate per unit area under a given hydraulic head, instead of permeability.

2.6.2 *Drain strength, flexibility and durability*

Stress-strain characteristics of drain filter and core should be compatible. The drain core or filter should not break when subjected to handling and installation stresses, which are typically higher than in-situ stresses in soil except in cases where sub-grade instability can occur. Therefore, a relatively high rupture strain is considered more important than high tensile strength of the drain.

Durability of the geosynthetic materials throughout the consolidation period is generally not a concern. However, if ground water is suspected to contain solvents or other chemical pollutants, the drain integrity needs to be checked.

Even though individual drain characteristics mentioned above help to select a particular drain, the most important consideration should be that the selected drain will help to achieve the required consolidation within the required period considering the whole system. No drain should be rejected on the basis of one characteristic alone, as there may be compensations when other factors are taken into consideration. For example, one drain may have relatively low filter permeability or discharge capacity which may be offset by a larger equivalent diameter (FHWA, 1986).

2.6.3 *Drain length*

Drain length should be sufficient to consolidate the soft soil deposit or portions of the deposit to the extent necessary to achieve the design objectives. In some cases, it may not be necessary to fully penetrate the compressible stratum to achieve the necessary shear strength gain or amount of consolidation. Also, as drain length becomes very large, say greater than 25m, additional length may not improve the consolidation rate considering the effects of drain resistance.

## 3 MAJOR PARAMETERS AFFECTING PERFORMANCE

The 'general' case for PVD design considers drain spacing, soil disturbance and drain resistance. It is noted that the greatest potential effect on $t_{90}$ is due to changes in $C_h$ and D (FHWA, 1986). The value of $C_h$, which can easily vary by a factor of 10, has the most dominant influence on $t_{90}$. D, which can vary by a factor of about 2 to 3, has a considerable influence due to the $D^2$ term. The influence of the properties of the disturbed zone ($k_s$ and $d_s$), although very difficult to quantify, can be very significant. The equivalent diameter, $d_w$ has only a minimal influence on $t_{90}$.

For typical values the ratio $F_r/F(n)$ is generally less than 0.05. Therefore, typically the theoretical effect of drain resistance is considerably less than the effect of drain spacing or soil disturbance. As eqn-3 suggests, the length of PVD may influence drain resistance. It is generally considered that except for PVD deeper than say, 25m, $F_r$ may not have much influence on PVD performance (FHWA, 1986).

## 4 SUGGESTED DESIGN PROCEDURE

Evaluation of effects of soil disturbance requires determination of ($k_h/k_s$) as well as diameter of the disturbed zone, ds. As mentioned above, research indicates that the ratio of ($k_h/k_s$) may vary from 2 to 5. Both soil sensitivity and condition of soil micro fabric have been found to affect this ratio. Careful consideration, engineering judgement and special testing are necessary to make realistic assessment of ($k_h/k_s$) for a particular project.

Except for very important major projects where time-settlement relationship has to be established with greater accuracy, such extensive investigation may prove time consuming and expensive. In any case, unless special techniques are adopted for soft soil sampling, soil sample disturbance is a reality and laboratory test results to establish $C_v$ and $k_h/k_v$ values are also subject to error. It may therefore be concluded that except for special projects, consideration of soil disturbance due to PVD installation as proposed in the 'general' case for PVD design may not be viable. In the light of this, the following procedure for PVD design is proposed.

### 4.1 Category- A

For the majority of projects involving ground improvement using PVD, the 'ideal' case for PVD design provides reasonable time-settlement relationship where smear and drain resistance effects are ignored. As mentioned earlier, laboratory determination of $k_h/k_v$ values compared well with back-calculated values from field instrument data giving $k_h/k_v$=2 to 3. For conservative analysis, a value of $C_h/C_v$=1 to 2 may be appropriate for use. This procedure may be adopted for PVD design to arrive at reasonably acceptable time-settlement relationship for the majority of ground improvement projects involving coastal marine clays and other soft coastal clays. However, it is important to consider precautions to minimize soil disturbance due to PVD installation and adopt recommended values for other parameters including PVD material parameters as discussed earlier.

### 4.2 Category- B

For more critical projects where more accurate time-consolidation prediction is required, extensive field and laboratory investigation will be required to establish $C_v$ and $k_h/k_v$ values applicable for a specific project site. As mentioned, evaluation of soil disturbance effects due to PVD installation is complex and may be established either by suitable laboratory investigations or by appropriate numerical analysis method. Recommended values for disturbance as mentioned earlier may be used in lieu.

## 5 CONCLUSIONS

1. Paper discusses theories and procedures currently available for PVD design. Significant parameters which affect PVD performance have been discussed.

2. As evaluation of soil disturbance due to PVD installation as well as drain resistance, which affect time-settlement prediction, is extremely complex and require special and expensive sampling, laboratory investigations and in-situ tests.

3. For the majority of projects involving PVD in coastal marine clays, the time-consolidation relationship can be predicted with sufficient accuracy considering the 'ideal' case, i.e. $C_v$ value from normal laboratory consolidation tests and considering $k_h/k_v$ = 2 or 3.

4. As disturbance to soil due to PVD installation is a major parameter affecting PVD performance, it is important to consider various measures to minimize soil disturbance during PVD installation.

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